Shocking Aluminum for Greater Understanding

LIVERMORE researchers have long investigated the properties of materials (especially metals) under extreme pressure by conducting shock compression experiments. These experiments help determine metals' fundamental properties, such as strength, and show how their behavior changes at pressures that occur in extreme environments such as explosive detonations or planetary interiors.

A Livermore team recently conducted experiments with a tabletop laser that afforded an unprecedented look into the physics of shock waves in aluminum. The team observed how aluminum responded to dynamic compression at strain rates of 10^{10} per second—1,000 times higher than previously measured. The study also showed that two important laws governing the behavior of shocked solids extend to higher strain rates than previously applied.

Strain rate is the dynamic (shock) compression applied to a material divided by the time to compress that material. Strain rates can be useful for inferring material strength properties, which are particularly important in stockpile stewardship for ensuring the reliability of the nation's nuclear deterrent. Although these rates have been historically difficult to measure, the Livermore team's laser-based system allows strain rates to be calculated much more easily.

Compression experiments apply either dynamic (gas-gun or laser) or static (diamond anvil cell) techniques to achieve high pressures. Each experimental platform yields slightly different but complementary information. While static compression can produce up to about 3 million times Earth's atmosphere, or 300 gigapascals, dynamic shock compression can produce pressures in the terapascal range.

For the past few years, the Livermore team has been examining various materials under extreme conditions that have included combinations of both static and dynamic pressure. For example, they have used their technique to dynamically compress deuterium that has been precompressed in a diamond anvil cell. By precompressing, they can control the initial density and thereby tune the final state. This method allows them to access a wide range of pressures and densities that may otherwise be difficult or impossible to achieve without precompression.

The Livermore team includes Jonathan Crowhurst, Michael Armstrong, Kim Knight, Joseph Zaug, and Elaine Behymer. Most of the scientists belong to Livermore's Extreme Chemistry Group, part of the Physical and Life Sciences Directorate. The group's collective expertise includes physics and chemistry under extreme conditions of pressure, temperature, and timescale. With funding from the Laboratory Directed Research and Development (LDRD) Program and the Department of Energy's Office of Science, the researchers are currently using lasers to study the time-dependent evolution of shock waves. These shock waves travel at supersonic speeds to produce irreversible "plastic" deformation where the

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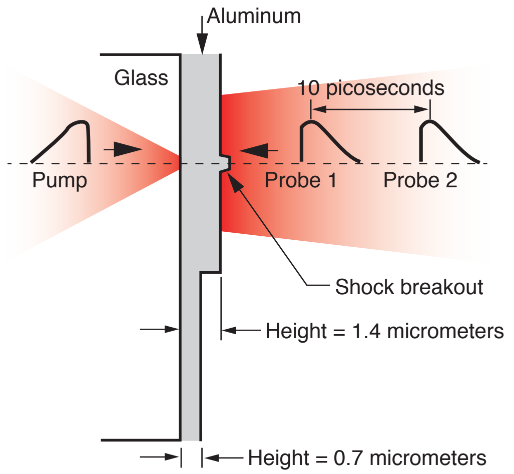
material is permanently altered. (In contrast, weaker shock waves produce elastic deformation, in which a material resumes its original shape and internal structure when a stress is removed.)

Little is understood about the behavior of metals during the initial phase of strong shock compressions. To resolve the details of a shock wave traveling through a solid in the first few 100-trillionths of a second, the team designed a compact, low-cost experimental laser system that simultaneously launches as well as probes shock waves in pure metal films. The system has also been used in experiments involving transparent materials, including deuterium and high explosives such as pentaerythritol teranitrate.



The experimental configuration consists of a stepped aluminum film deposited in two thicknesses onto a glass slide. The lower aluminum step measures about 0.7 micrometers, and the upper step is about 1.4 micrometers. A 270-picosecond pulse derived from the 100-femtosecond output of a tabletop laser produces and measures the shock waves driven into each step (test of upper step shown) with a time resolution of about 10 picoseconds (1 picosecond equals 10^{-12} seconds, 1 femtosecond equals 10^{-15} seconds). A pair of laser probe pulses measured the acceleration of the free aluminum surface driven by the shock wave as well as the strain rate.

Technique Tracks Evolution

In one set of experiments, the team obtained data on the dynamic strength of aluminum and the evolution of shock waves at the highest strain rates recorded to date—10^{10} per second. The team used the experimental results to test for the first time at ultrahigh strain rates the validity of two fundamental scaling laws.

The researchers chose aluminum because it is commonly used in compression experiments. In addition, the team had been studying it in experiments in which aluminum was precompressed in a diamond anvil cell before being shocked by a laser. No strain rate data have existed for aluminum subjected to rates greater than 10^7 per second, and even recent theoretical models were based on data obtained 40 years ago.

The experimental sample consisted of a stepped aluminum film deposited in two thicknesses onto a glass slide. The lower aluminum step measured about 0.7 micrometers, while the upper step measured about 1.4 micrometers.

The scientists used an instrument designed and built by Armstrong to both produce and characterize shock waves on an ultrafast timescale. The instrument is based on a stable commercial laser system that can generate compression waves reproducibly. “This ability is critical to the measurement of shock wave speeds using this technique,” Armstrong says. For the experiments, compression waves were driven into each of two steps in a metal sample and characterized with a time resolution of about 10 picoseconds. The peak of the pump pulse centered at 800-nanometer wavelength, with pulse duration of about 270 picoseconds and rise time of about 12 picoseconds. Pump energies ranged between 100 and 150 microjoules.

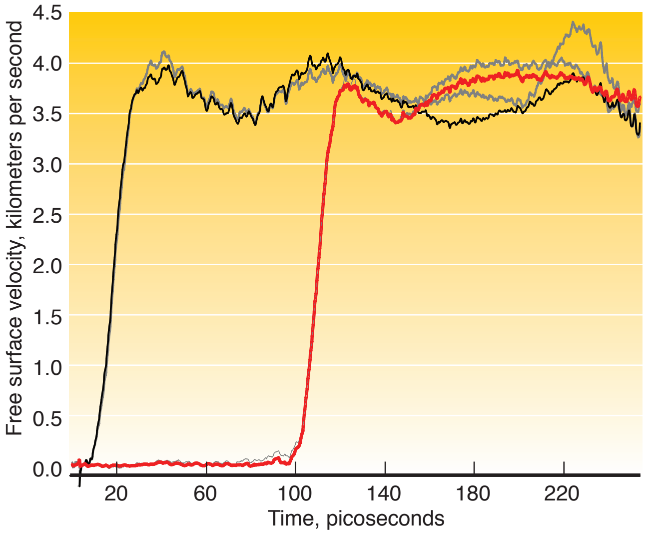
The highly repeatable laser directs nearly identical shots on two different thicknesses. A pair of laser probe pulses measure the acceleration of the free aluminum surface driven by the shock wave as well as the strain rate. Using this technique, researchers measure a Doppler shift in light reflected from a moving surface, which is proportional to the speed of the surface. When a shock wave hits the aluminum free surface, the surface starts to move, which generates an optical phase shift between a pair of probe pulses. This phase shift changes an interference pattern generated by the probe pulses, which is detected through spectral interferometry. The diagnostic thus records the early time history of the compression wave. Because the timing of the pump pulse in relationship to the two probe pulses is very accurate, the results obtained are highly reproducible.

The team measured stresses that reached 43 gigapascals (or 430,000 times Earth’s atmospheric pressure) in some tens of picoseconds, which corresponds to strain rates in excess of 10^{10} per second. The experimental data reveal at lower strain rates a compression wave consisting of an initial elastic zone followed by a plastic zone, and then at higher strain rates only an apparent plastic zone. The shock velocity was obtained by dividing the known thickness of the upper step by the difference in shock-wave arrival times at the two thicknesses.

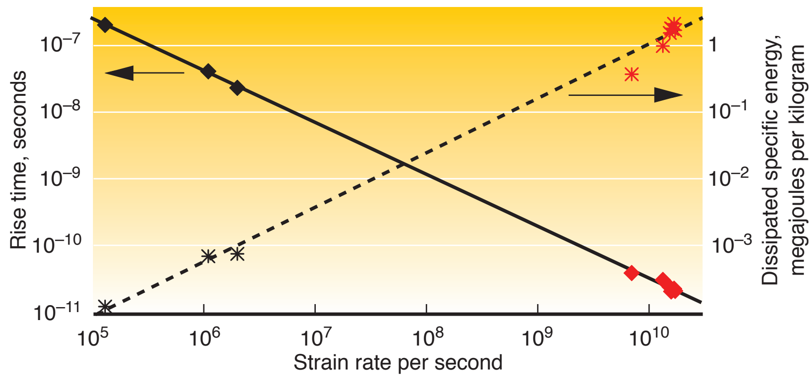
Crowhurst notes that the resolved time and length scales of the experiments are similar in scale to molecular dynamics simulations, which depict the interactions of atoms and molecules in less than a nanosecond (billionth of a second). As a result, the team’s findings are expected to increase the accuracy of current models.

Validating Two Laws

In achieving their experimental goals of examining the shock properties of aluminum at high strain rates and extremely short timescales, the scientists also confirmed the validity of two fundamental scaling laws that had been previously demonstrated at strain rates 1,000 times lower. The historic lack of sufficient time resolution had precluded testing the laws at high strain rates. “The details of how solid materials rapidly deform on submicrometer length scales have been the subject of speculation for decades,” Armstrong says. “For the first time, our experiments can test



This graph shows a rapid rise in the strain rate resulting from strong laser pulses directed at an aluminum film measuring 0.7 micrometers thick and an aluminum film measuring 1.4 micrometers thick. Black line is a three-shot average at the 0.7-micrometer thickness, and red line is a three-shot average at the 1.4-micrometer thickness. Gray lines are examples of single shocks.



Results confirmed the validity of two fundamental scaling laws previously demonstrated at much lower strain rates. The first law states that the energy dissipated by a shock wave (stars), multiplied by the time over which it takes place (diamonds), is a constant. The second law states that the strain rate is proportional to the fourth power of the peak stress for steady-state shock waves. Combining the ultrahigh strain-rate measurements with results from gas-gun experiments at lower strain rates indicated that both laws hold over at least five orders of magnitude (10^5–10^{10} per second) of strain rate. Red denotes current data, and black denotes previous data.

fundamental scaling laws on time and length scales where they may start to break down at strain rates that are orders of magnitude greater than previously examined."

The first scaling law, the invariance of dissipative action, states that the energy dissipated by a shock wave multiplied by the time over which it occurs, is a constant. The second, the fourth power law, states that the strain rate is proportional to the fourth power of the peak stress (that is, the peak stress multiplied by itself four times) for steady-state shock waves. The team tested the laws by combining their ultrahigh strain-rate measurements with results from lower-strain-rate gas-gun experiments on thicker samples of aluminum. The team concluded that both the fourth-power scaling and the invariance of the dissipative action are maintained at ultrahigh strain rates of up to 10^{10} per second, and that both relationships hold for at least five orders of magnitude (10^5–10^{10} per second).

"Gas-gun experiments remain the 'gold standard' for studying shocked materials," says Armstrong. However, experimenters have yet to obtain the same time resolution with gas guns as those using lasers. "Our experiments fill a niche; they complement other efforts."

Crowhurst notes that these small-scale compression experiments are relatively inexpensive, and the shots are easily reproducible. In fact, because such little material is required (the shocked regions on the aluminum surface can only be clearly seen under a microscope), hundreds of shots can be done on the same sample. As a result, the team is exploring the design of an automated process for conducting hundreds of experiments per hour.

Currently, the team is performing laser-shocked compression experiments on other metals such as iron and vanadium. Experiments on aluminum are also being conducted with the goal of achieving strain rates of up to 10^{12} per second. Meanwhile, Armstrong is working on an LDRD-funded project to study shocked deuterium, an isotope of hydrogen. Other shock-compression experiments are being conducted as part of the Department of Defense's Joint Munitions Command. Because these experiments involve extremely small amounts of high explosives, they do not present the potential hazards of larger-scale experiments.

Scientists from other national laboratories have visited the Laboratory to observe the experimental setup and study the team's data-analysis procedures. "Our work builds on previous research at other national labs and universities," says Crowhurst. "We believe that the number of groups who have adopted the ultrafast approach to study shock waves will continue to grow. The technique has a bright future." Scientists can expect even more insight into the ultrafast aspects of shock compression and, in turn, a deeper understanding of materials under pressure.

—Arnie Heller

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